Lifetime difference in D^0-$\overline{D}^0$ mixing within R-parity-violating SUSY

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We re-examine constraints from the evidence for observation of the lifetime difference in D^0-$\overline{D}^0$ mixing on the parameters of supersymmetric models with R-parity violation (RPV). We find that RPV SUSY can give large negative contribution to the lifetime difference. We also discuss the importance of the choice of weak or mass basis when placing the constraints on RPV-violating couplings from flavor mixing experiments.

1. Introduction

Meson-antimeson mixing is an important vehicle for indirect search of New Physics (NP) [1]. $D^0 - \overline{D}^0$ mixing [2] is the only available meson-antimeson mixing in the up-quark sector. The fact that the search is indirect and complimentary to existing constraints from the bottom-quark sector actually provides parameter space constraints for a large variety of NP models [3, 4].

One can write the normalized lifetime difference in $D^0 - \overline{D}^0$ mixing, $y_{\rm D} \equiv \Delta\Gamma_{\rm D}/(2\Gamma_{\rm D})$, as an absorptive part of the $D^0 - \overline{D}^0$ mixing matrix [5],

$$y_D = \frac{1}{\Gamma_{\rm D}} \sum_n \rho_n \langle \overline{D}^0 | \mathcal{H}_w^{\Delta C=1} | n \rangle \langle n | \mathcal{H}_w^{\Delta C=1} | D^0 \rangle, \quad (1.1)$$

where ρ_n is a phase space function that corresponds to a charmless intermediate state n. This relation shows that $\Delta\Gamma_{\rm D}$ is driven by transitions $D^0, \overline{D}^0 \to n$, *i.e.* physics of the $\Delta C = 1$ sector.

It was recently shown [4] that $D^0 - \overline{D}^0$ mixing is a rather unique system, where the lifetime difference can be used to constrain the models of New Physics[1]. This stems from the fact that there is a well-defined theoretical limit (the flavor $SU(3)$-limit) where the SM contribution vanishes and the lifetime difference is dominated by the NP $\Delta C = 1$ contributions. In real world, flavor $SU(3)$ is, of course, broken, so the SM contribution is proportional to a (second) power of m_s/Λ, which is a rather small number. If the NP contribution to $y_{\rm D}$ is non-zero in the flavor $SU(3)$-limit, it can provide a large contribution to the mixing amplitude.

To see this, consider a D^0 decay amplitude which includes a small NP contribution, $A[D^0 \to n] = A_n^{\rm (SM)} + A_n^{\rm (NP)}$. Experimental data for D-meson decays are known to be in a decent agreement with the SM estimates [7, 8]. Thus, $A_n^{\rm (NP)}$ should be smaller than (in sum) the current theoretical and experimental uncertainties in predictions for these decays.

One may rewrite equation (1.1) in the form (neglecting the effects of CP-violation)

$$y_D = \sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{\rm (SM)} \bar{A}_n^{\rm (SM)} + 2 \sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{\rm (NP)} \bar{A}_n^{\rm (SM)} + + \sum_n \frac{\rho_n}{\Gamma_{\rm D}} A_n^{\rm (NP)} \bar{A}_n^{\rm (NP)} \quad (1.2)$$

The first term in this equation corresponds to the SM contribution, which vanishes in the $SU(3)$ limit. In ref. [4], as well as in the superseding papers [9, 10], the last term in (1.2) has been neglected, thus the NP contribution to $y_{\rm D}$ comes there solely from the second term, due to interference of $A_n^{\rm (SM)}$ and $A_n^{\rm (NP)}$. While this contribution is in general non-zero in the flavor $SU(3)$ limit, in a large class of (popular) models it actually is [4, 10]. Then, in this limit, $y_{\rm D}$ is completely dominated by pure $A_n^{\rm (NP)}$ contribution given by the last term in eq. (1.2)! It is clear that the last term in equation (1.2) needs more detailed and careful studies, at least within some of the NP models.

Indeed, in reality, flavor $SU(3)$ symmetry is broken, so the first term in Eq. (1.2) is not zero. It has been argued [11] that in fact the SM $SU(3)$-violating contributions could be at a percent level, dominating the experimental result, $y_D^{exp} = (0.73 \pm 0.18)\%$ [12]. The SM predictions of y_D, stemming from evaluations of long-distance hadronic contributions, are rather uncertain. While this precludes us from placing explicit constraints on parameters of NP models, it has been argued that, even in this situation, an upper bound on the NP contributions can be placed [3] by displaying the NP contribution only, i.e. as if there were no SM contribution at all. This procedure is similar to what was traditionally done in the studies of NP contributions to $K^0 - \overline{K}^0$ mixing, so we shall employ it here too.

In order to evaluate importance of the NP contribution, as the flavor $SU(3)$ is broken, counting of suppression powers of m_s/m_c for the SM contribution versus those of M_W^2/M_{NP}^2 of the NP contribution must be performed. For the last term in eq. (1.2) to be essential, the following approximate rule applies: $M_W^4/M_{NP}^4 > m_s^2/m_c^2$. This term is of the primary importance here: the second term in (1.2) is proven to be $\lesssim 10^{-4}$ in the most popular SM extensions [4, 10, 13]

[1] A similar effect is possible in the bottom-quark sector [6].

and, hence, negligible in general.

The talk is based on the results presented in [14]. We revisit the problem of the NP contribution to $y_{\rm D}$ and provide constraints on R-parity-violating supersymmetric (SUSY) models as a primary example. It has been recently argued in [13] that within $\not{R}$- SUSY models, new physics contribution to $y_{\rm D}$ is rather small, mainly because of stringent constraints on the relevant pair products of RPV coupling constants. However, this result has been derived neglecting the transformation of these couplings from the weak isospin basis to the quark mass basis. This approach seems to be quite reasonable for the scenarios with the baryonic number violation. However, in the scenarios with the leptonic number violation, transformation of the RPV couplings from the weak eigenbasis to the quark mass eigenbasis turns to be crucial, when applying the existing phenomenological constraints on these couplings.

We show in that within R-parity-breaking supersymmetric models with the leptonic number violation, new physics contribution to the lifetime difference in $D^0-\overline{D}^0$ mixing may be large, due to the last term in eq. (1.2). When being large, it is negative (if neglecting CP-violation), i.e. opposite in sign to what is implied by the recent experimental evidence for $D^0-\overline{D}^0$ mixing.

2. R-Parity Breaking Interactions: Weak vs Mass Eigenbases

We consider a general low-energy supersymmetric scenario with no assumptions made on a SUSY breaking mechanism at the unification scales ($\sim (10^{16}-10^{18}) GeV$). The most general Yukawa superpotential for an explicitly broken R-parity supersymmetric theory is given by

$$W_{\not{R}} = \sum_{i,j,k}\left[\frac{1}{2}\lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \right. \\ \left. +\frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k\right] \quad (2.1)$$

where L_i, Q_j are $SU(2)_L$ weak isodoublet lepton and quark superfields, respectively; E^c_i, U^c_i, D^c_i are $SU(2)$ singlet charged lepton, up- and down-quark superfields, respectively; λ_{ijk} and λ'_{ijk} are lepton number violating Yukawa couplings, and λ''_{ijk} is a baryon number violating Yukawa coupling. To avoid rapid proton decay, we assume that $\lambda''_{ijk}=0$ and work with a lepton number violating $\not{R}$- SUSY model.

For meson-to-antimeson oscillation processes, to the lowest order in the perturbation theory, only the second term of (2.1) is of the importance. After transforming quark fields from the weak isospin basis (used in eq. (2.1) to the quark mass eigenbasis, the relevant R-parity breaking part of the Lagrangian may be presented in a following form:

$$\mathcal{L}_{\not{R}} = -\sum_{i,j,k}\widetilde{\lambda}'_{ijk}\left[\widetilde{e}_{i_L}\bar{d}_{k_R}u_{j_L} + \widetilde{u}_{j_L}\bar{d}_{k_R}e_{i_L} + \right. \\ \left. +\widetilde{d}^*_{k_R}\bar{e}^c_{i_R}u_{j_L}\right] + \sum_{i,j,k}\lambda'_{ijk}\left[\widetilde{\nu}_{i_L}\bar{d}_{k_R}d_{j_L} + \right. \\ \left. \widetilde{d}_{j_L}\bar{d}_{k_R}\nu_{i_L} + \widetilde{d}^*_{k_R}\bar{\nu}^c_{i_R}d_{j_L}\right] + h.c. \quad (2.2)$$

where

$$\widetilde{\lambda}'_{ijk} \;=\; V^*_{jn}\;\lambda'_{ink} \quad (2.3)$$

with V being the CKM matrix.

Very often in the literature (see e.g. [4], [13], [15]-[17]) one neglects the difference between λ' and $\widetilde{\lambda}'$, based on the fact that diagonal elements of the CKM matrix dominate over non-diagonal ones, i.e.

$$V_{jn} = \delta_{jn} + O(\lambda) \qquad \text{so} \qquad \widetilde{\lambda}_{ijk} \approx \lambda'_{ijk} + O(\lambda) \quad (2.4)$$

where $\lambda = \sin\theta_c \sim 0.2$, with θ_c being the Cabibbo angle.

Notice that relation (2.4) is valid if only there is *no hierarchy* in couplings λ'. On the other hand, the existing strong bounds on pair products $\lambda'\times\lambda'$ (or $\widetilde{\lambda}'\times\widetilde{\lambda}'$) [15, 16, 18] and relatively loose bounds on individual couplings λ' [18] suggest that such a hierarchy may exist. We have shown in the original work [14] that pair products $\widetilde{\lambda}'\times\widetilde{\lambda}'$ may be orders of magnitude greater than corresponding products $\lambda'\times\lambda'$. This fact plays a crucial role in our analysis.

In what follows, neglecting the transformation of RPV couplings from the weak eigenbasis to the quark mass eigenbasis would lead to overestimate of existing phenomenological bounds on these couplings. As a result, one would get that within R-parity violating supersymmetric models, NP contribution to the lifetime difference in $D^0-\overline{D}^0$ mixing is rather negligible [13]. Yet, this result is true if no hierarchy in the values of the relevant RPV couplings exist. More generally, in presence of such hierarchy, due to rather loose constraints on the relevant $\widetilde{\lambda}'\times\widetilde{\lambda}'$ products, RPV SUSY contribution to $y_{\rm D}$ may be of the same order or even exceed the experimental value.

3. Dominant Contribution to $y_{\rm D}$

Within R-parity violating SUSY models, the dominant contribution to the lifetime difference in $D^0-\overline{D}^0$ mixing comes from the part of $D^0-\overline{D}^0$ transition amplitude that occurs when both of $\Delta C=1$ transitions are generated by NP interactions, due to exchange of a charged slepton (see Fig. 1). This contribution to $y_{\rm D}$,

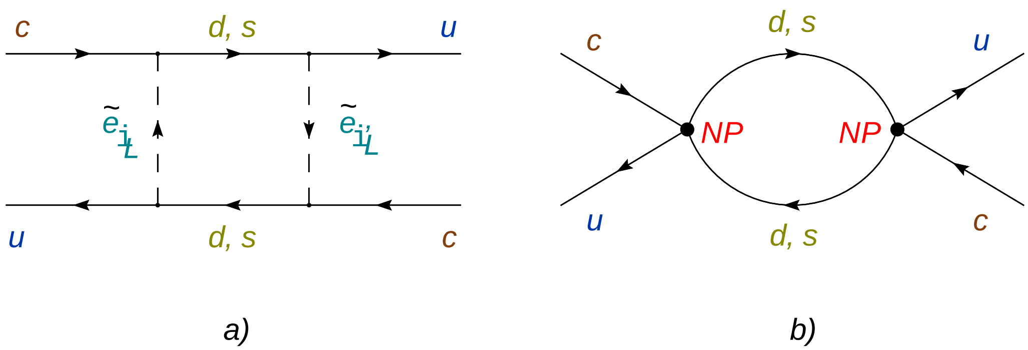

Figure 1: Diagrams giving the dominant contribution to $y_{\rm D}$ a) within the full electroweak theory; b) within the low-energy effective theory.

denoted here by $y_{\tilde\ell\tilde\ell}$, is given by the following formula:

$$y_{\tilde\ell\tilde\ell} \approx \frac{-m_c^2 f_D^2 B_D m_D}{288\pi\Gamma_D m_{\tilde\ell}^4}\left[\frac{1}{2}+\frac{5}{8}\frac{\bar B_D^S}{B_D}\right]\left[\,\lambda_{ss}^2+\lambda_{dd}^2\right] \quad (3.1)$$

where f_D is D-meson decay constant, B_D and $\bar B_D^S$ are vacuum saturation factors [3] and

$$\lambda_{ss} \equiv \sum_i \,\widetilde\lambda'^*_{i12}\,\widetilde\lambda'_{i22}, \quad \lambda_{dd} \equiv \sum_i \,\widetilde\lambda'^*_{i11}\,\widetilde\lambda'_{i21} \quad (3.2)$$

To simplify the calculations, we assumed that all the sleptons are nearly degenerate, i.e. $m_{\tilde\ell_i} = m_{\tilde\ell}$.

Note that $y_{\tilde\ell\tilde\ell}$ is non-vanishing in the exact flavor $SU(3)$ limit. Also, present experimental data still allow for the slepton masses to be $\sim 100\ GeV$ [19]. Finally, present phenomenological constraints on the coupling pair products λ_{ss} and λ_{dd} are rather loose, when taking into account the transformation of RPV couplings from the weak eigenbasis to the quark mass eigenbasis (see [14] for more details). One has $|\lambda_{ss}| < 0.29$, $|\lambda_{dd}| < 0.29$ or $\lambda_{ss}^2 < 0.0841$, $\lambda_{dd}^2 < 0.0841$. Thus, as it follows from our discussion above, $y_{\tilde\ell\tilde\ell}$ may be quite large.

Indeed, the numerical analysis yields

$$-0.12\left(\frac{100GeV}{m_{\tilde\ell}}\right)^4 \le y_{\tilde\ell\tilde\ell} < 0 \quad (3.3)$$

In other words, $|y_{\tilde\ell\tilde\ell}|$ may be $\sim 10^{-1}$, if $m_{\tilde\ell} = 100$ GeV.

Thus, within R-parity breaking supersymmetric models with the lepton number violation, new physics contribution to $D^0 - \bar D^0$ lifetime difference is *predominantly negative* and may exceed in absolute value the experimentally allowed interval. In order to avoid a contradiction with the experiment ($y_D^{exp} = (0.73 \pm 0.18)\%$ [12]), one must either have a large positive contribution from the Standard Model, or place severe restrictions on the values of RPV couplings. As it follows from [11], y_{SM} may be as large as $\sim 1\%$. In what follows, $|y_{new}|$ must be $\sim 1\%$ or smaller as well. If $|y_{new}| \sim 1\%$, then, imposing condition

$$-0.01 \le y_{new} \approx y_{\tilde\ell\tilde\ell} \quad (3.4)$$

one obtains that either $m_{\tilde\ell} > 185$GeV, or if $m_{\tilde\ell} \le 185$GeV, condition (3.4) implies new bounds on λ_{ss} and λ_{dd}:

$$|\lambda_{ss}| \le 0.082\left(\frac{m_{\tilde\ell}}{100GeV}\right)^2 \quad (3.5)$$

$$|\lambda_{dd}| \le 0.082\left(\frac{m_{\tilde\ell}}{100GeV}\right)^2 \quad (3.6)$$

It is interesting to compare the restrictions on λ_{ss} and λ_{dd}, given by (3.5), (3.6), with those derived in [3] from study of $D^0 - \bar D^0$ mass difference. Bounds of [3] on λ_{ss} and λ_{dd} turn to be about 20 times stronger than our ones. On the other hand, constraints of ref. [3] on the RPV coupling products are derived in the limit when the pure MSSM contribution to Δm_D is negligible. Generally speaking, the MSSM contribution to $D^0 - \bar D^0$ mass difference is significant even for the squark masses being about 2TeV. In what follows, the destructive interference of the pure MSSM and R-parity violating sector contributions may distort bounds of ref. [3], making them inessential as compared to (3.5), (3.6).

Contrary to this, pure MSSM contributes to $\Delta\Gamma_D$ only in the next-to-leading order via two-loop dipenguin diagrams. Naturally, this contribution is expected to be small. In what follows, unlike those of ref. [3], our constraints on the RPV coupling products λ_{ss} and λ_{dd}, given by (3.5), (3.6), seem to be insensitive or weakly sensitive to assumptions on the pure MSSM sector of the theory.

Thus, our main result is that within R-parity breaking supersymmetric theories with the leptonic number violation, new physics contribution to $\Delta\Gamma_D$ may be quite large and is predominantly negative.

4. Conclusion

We computed a possible contribution from R-parity-violating SUSY models to the lifetime difference in $D^0 - \overline{D}^0$ mixing. The contribution from RPV SUSY models with the leptonic number violation is

found to be negative, i.e. opposite in sign to what is implied by recent experimental evidence, and possibly quite large, which implies stronger constraints on the size of relevant RPV couplings.

We discussed currently available constraints on those couplings (especially on the products of them), available from kaon mixing and rare kaon decays. We emphasize that the use of these data in charm mixing has to be done carefully separating the constraints on RPV couplings taken in the mass and weak eigenbases, given the gauge and CKM structure of $D^0 - \overline{D}^0$ mixing amplitudes.

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